

# Seismo-ionospheric effects associated with 'Chelyabinsk' meteorite during the first 25 minutes after its fall

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September 23, 2014

## Abstract

This paper presents the properties of ionospheric irregularities elongated with Earth magnetic field during the first 25 minutes after the fall of the meteorite 'Chelyabinsk' experimentally observed with EKB radar of Russian segment of the SuperDARN.

It is shown that 40 minutes before meteor fall the EKB radar started to observe powerful scattering from irregularities elongated with the Earth magnetic field in the F-layer. Scattering was observed for 80 minutes and stopped 40 minutes after the meteorite fall.

During 9-15 minutes after the meteorite fall at ranges 400-1200 km from the explosion site a changes were observed in the spectral and amplitude characteristics of the scattered signal. This features were the sharp increase in the Doppler frequency shift of the scattered signal corresponding to the Doppler velocities about 600 m/s and the sharp increase of the scattered signal amplitude. This allows us to conclude that we detected the growth of small-scale ionospheric irregularities elongated with the Earth magnetic field at E-layer heights. Joint analysis with the seismic data and numerical modeling shows that the observed effect is connected with the passage of secondary acoustic front formed by supersonic seismic ground wave from the 'Chelyabinsk' meteorite.

As a possible explanation the growth of elongated ionospheric irregularities may be caused by the passage of the high-speed acoustic wave in the ionosphere in the presence of high enough background electric field.

# 1 Introduction

The fall of 'Chelyabinsk' meteorite 03:20UT 15/02/2013 was accompanied by a large number of dynamic ionospheric [Tertyshnikov et al 2013, Givishvili et al 2013, Gokhberg et al 2013, Berngardt et al 2013, Yang et al 2014], atmospheric [Le Pichon et al 2013, Gorkavyi et al 2013] and seismic [Tauzin et al 2013] phenomena. The well known dynamic ionospheric effects include formation of midscale radially traveling ionospheric disturbances (MSTIDs) at F-layer heights, detected directly by EKB coherent radar and GPS network [Berngardt et al 2013b, Gokhberg et al 2013, Yang et al 2014] (at distances less than 1000 km). Also an indirect evidence of the same radial waves at E-layer heights [Kutelev and Berngardt 2013] (at distances less than 700 km) were found. The analysis shows that the average speed of this MSTIDs, observed at 500-1000 km distances from the epicenter, is 400m/s and 200 m/s [Kutelev and Berngardt 2013]. Analysis of GPS data provides estimates of the average velocity of 140 m/s [Berngardt et al 2013], 400 m/s [Berngardt et al 2013b, Yang et al 2014] and 800 m/s [Yang et al 2014]. Basic wave effects thus appear between 20-th and 80-th minutes after the explosion.

Significant ionospheric effects during the first 20-25 minutes after the fall at close distances from the explosion site (about 500-700km) were not investigated yet.

In this paper we studied the ionospheric effects observed in the first 25 minutes after the meteorite fall in E- and F-layers of the ionosphere. The nearest zone to the explosion site (500-700km) is potentially the most disturbed. Therefore the study of ionospheric effects in this region requires high spatial and temporal resolutions simultaneously, which is currently provided only by EKB radar.

The EKB radar is the first coherent decameter radar of Russian segment of SuperDARN [Chisham et al 2007]. It was bought, assembled and started by ISTP SB RAS for monitoring in the middle of December 2012. This allowed us to get a big amount of the ionospheric data during the meteorite fall, as well as before and after the fall with high spatially-temporary resolution. EKB radar is located around 200 km to north-west from the meteorite explosion site. The radar is the analog of CUTLASS radar [Lester et al 2004] positioned by ISTP SB RAS at 'Arti' observatory of Institute of Geophysics, Ural Branch of Russian Academy of Sciences (56o26 N, 58o34 E).

The basis of the radar functionality is monitoring of back-scattered signal characteristics simultaneously in back-oblique sounding mode (BOS, ground backscatter) and the backscattering from small-scale irregularities mode (BS). This allows to make simultaneous estimation of both the characteristics of the background ionosphere in BOS mode, and the characteristics of small-

scale irregularities in BS mode. The antenna system of the radar is a phased array with azimuthal scan sector of about 50 degrees and with a mainlobe azimuthal width of about 3 degrees. Scanning the entire sector is made by iterating over 16 directions counterclockwise. The scanning takes for about 60 seconds, with probing in each of the 16 fixed beam directions for about 4 seconds.

During the observations the radar worked with 60km range resolution in the range of distances 400-3500km. The area of a meteorite explosion and fall was located 200km to the south of the radar in the area of the antenna pattern backlobe. The geometry of the experiment is shown at Fig.1. Further in the paper we will refer the time and place of maximum luminosity 03:20:33 UT as the moment and site of the explosion, and refer the place of finding the main meteorite fragment (Chebyrkul Lake) as the place of the fall.

Radar EKB has a unique spatial and temporal resolution, allowing detailed study of many ionospheric effects during the meteorite 'Chelyabinsk' fall. Some of the ionospheric effects based on the radar data are described in [Berngardt et al 2013, Berngardt et al 2013b, Kutelev and Berngardt 2013]. All these papers are focused to an analysis of the effects in the electron density profile during the first 2 hours after the fall. These effects mainly related with the changes in the background electron density with the spatial scales exceeding the size of the Fresnel zone.

In this paper we will study the effects of amplifying short-lived small-scale irregularities with hundred-meter spatial scales, smaller than the Fresnel radius, that hardly be detected by other ionospheric instruments.

## 2 Ionospheric observations

According to the literature [Berngardt et al 2013, Berngardt et al 2013b, Alpatov et al 2013, Givishvili et al 2013, Gokhberg et al 2013, Tertyshnikov et al 2013] the meteorite fall was characterized by a relatively quiet geomagnetic and seismic conditions, as well as the absence of significant solar flares. Except for regular disturbances associated with a passage of the solar terminator, and with the impact of the previous day 14/02/2013, characterized by weak geomagnetic disturbance the average ionospheric situation was quiet. Therefore, ionospheric dynamics should be similar to the dynamics of the nearest quiet days. This allow us to differ the effects associated with the explosion and the fall of the meteorite from a regular daily dynamics with a high degree of confidence. To highlight effects of irregular dynamics in the power of the scattered signal, associated with regular processes in the ionosphere, we conducted an analysis of 15/02/2013 data relative to the same quiet (the

reference) days 9-12,18 / 02/2013, following to [Berngardt et al 2013b].

The main technique for detection of irregular effects is to analyze power of the received signal 15/02/2013, and to compare it with the power averaged over the the reference days. For qualitative analysis the scattered signal power were averaged over the entire field-of-view azimuths as a function of time and distance. To simplify the qualitative analysis we consider only the cases of high level of scattered signal power exceeding the noise level. Fig.2A shows the overall picture of the average power of the scattered signal, averaged over the field-of-view azimuths during 15/02/2013, and Fig.2B - the same but averaged over the reference days. Region I studied in detail in [Kutelev and Berngardt 2013]. In this paper we will study in detail the region II, associated with the effect of scattering from small-scale F-layer irregularities during the period 02:45-04:00UT.

According to EKB radar data, 40 minutes before the meteorite fall a signal was observed coming from the ranges 500-1000km (Fig.2A, region II). Earlier, in the work [Berngardt et al 2013b] it was suggested that a possible reason for the formation of such a signal was increase of the electron density in the E-layer of the ionosphere. Detailed analysis, however, showed that the spectral width of the signal often exceeds 100-200 m/s, and the signal itself is observed at a distance equal to half the distance the ground backscatter signal. This suggests that the cause of the signal between 02:45-04:00UT is the scattering by F-layer irregularities elongated with the Earth magnetic field.

The main mechanism of formation of these irregularities are usually considered plasma instabilities, particle precipitation and turbulence in the ionospheric plasma [Fejer and Kelley 1980]. The growth of such irregularities, as a rule, requires a sufficiently high electric field at ionospheric heights, that usually associated with increased activity in the near-Earth space.

It should be noted that when the background electric field exceed 25mV/m, there are not only elongated irregularities in the F-layer grown, but also irregularities in the E-layer are grown, which are associated with Farley-Buneman instabilities [Farley 1963, Buneman 1963]. Such irregularities in E-layer in a simple manner can be separated from the F-layer irregularities because they often observed at a fixed radar range, not dependent on the refraction effects, that are typical for radio signals propagation in the F-layer. Since position of the region II depend on time, as it predicted by refraction effect, the region II corresponds to F-layer scattering. So E-layer irregularities has not been observed before meteorite fall (02:40-03:20UT) and it can be assumed that the background electric field during 02:40-03:20UT was strong enough to generate irregularities in the F-layer, but did not exceed 25mV/m necessary for the generation of E-layer irregularities.

Let us analyze in detail the behavior of the scattered signal at EKB radar during  $\pm 40$  minutes of the explosion. Currently, for the estimating of the parameters of ionospheric irregularities from the SuperDARN scattered signal the three basic algorithms are used - FitACF, FitACFex2 and LMFit [Ribeiro et al 2013]. Fig.3 shows the result of analysis by all three programs during 15/02/2013. Fig.3A shows the number of 'good' data per 1 minute at all lags corresponding to the distances 500-1200km from the radar, at which the scattering from elongated E-layer irregularities can be observed. The 'good' data means that result of calculations gives physically meaningful parameters - spectral width greater than 0, and signal-to-noise ratio greater than 0dB. The average power of the scattered signal calculated from the good data, is shown at Fig.3B.

Complex structure of the spectra is shown at Fig.4. The spectra obtained by integration over the radar ranges 800-1200km and subtracting mean noise. One can see that during 9-15 min. after the meteorite explosion spectra zero-drift becomes narrower, and spectra itself becomes more complex, having up to 3-peaks, that explains difficulty in their interpretation by standard programs. One can see, that most powerful and high-speed response is observed at 9th-10th minutes after the meteorite fall. Less powerful effects are also observed at 7-th minute.

It can be seen from the Fig.3 that during the period from 7 to 17 minutes after the meteorite explosion all the algorithms show a sharp decrease in the number of 'good' data. The results of processing by the most recent and accurate FitACFex2 and LMFit programs [Ribeiro et al 2013] show a dramatic increase in the power of the scattered signal at 10, 15, 19 and 23-24 minutes after explosion. A sharp increase in the signal power at 10 and 19 minutes can also be seen from FitACF program results. Monotonic increase in signal power after 15 minute is caused by the regular ionospheric processes in the dawn time.

This suggests that in the period from 10 to 17 minute the scattered signal becomes quite complicated and can not be accurately processed by standard techniques based on the assumptions of FitACF, FitACFex2 and LMFit models, and can be analyzed only qualitatively. At the same time, it is obvious that at 10, 15, 19 and 23 minutes the amplitude of the scattered signal sharply increased, which indicates the possible growth of small-scale scattering irregularities during these periods.

The main mechanism for the formation of the E-layer irregularities at mid-latitudes is usually the growth of two-stream instabilities [Farley 1963, Buneman 1963], usually classified as Type I scattering, characterized by high drift velocities equal to or greater than the ion-acoustic speed in the ionosphere.

Fig.5 shows the values of the Doppler velocity computed by the scattered signal as a function of delay after the explosion and distance from the radar. Calculations were carried out by three different programs: FitACF, FitACFex2 and LMFit. Circles, triangles and crosses represent the values computed by algorithms, lines - the medians over the 4 adjacent values, allowing to get rid of the occasional mistakes and get smoothed values. From Fig.5 it is seen that all three algorithms show an increase in Doppler velocity at ranges 500-900km during 7th-14th minutes after the explosion, with an absolute maximum at 9th-10th minute.

As it has been shown (Fig.4) the scattered signal at this time is quite complicated, and the parameters of the scattered signal are harder to determine than usually. Nevertheless, the fact that different methods shows similar high mean values of Doppler shift, allows to suggest that at 10-th minute after the explosion at ranges 500-1200km from the epicenter at EKB radar we actually observed scattered signal with high Doppler shifts, corresponding to the scattering from elongated E-layer irregularities of Type I (Farley-Buneman).

### 3 Seismo-ionospheric processes

Numerical simulation of the acoustic signal in the ionosphere, from the source at 41km altitude, corresponding to the first intense flare of the bolide [Borovicka et al 2013] is shown at Fig.6. The simulation showed that the delay of the acoustic signal propagating directly over the path meteor-observation point at 250 km height (for the minimum observed radar range - 500 km) is 17-18 minutes, and at the height 90-120km for the same distance - at least 23 minutes. So the propagation of this 'primary' acoustic wave from the meteorite trajectory can not explain the effects at ranges 500-1200km, observed with a delay of less than 17 minutes from explosion.

Known effect of the flyover and the explosion of the meteorite is the formation of acoustic [Popova et al 2013, Le Pichon et al 2013] and seismic [Tauzin et al 2013] waves. Seismic waves observed during meteorite falls, are usually caused by three reasons - by striking massive body to the earth's surface, by meteorite explosion and by coming the acoustic wave produced by the passage of a supersonic body in the upper atmosphere. Review of techniques for the recovery of the trajectory of a meteorite based on these effects is shown, for example in [Edwards et al 2008].

The mass of the 'Chelyabinsk' meteorite fragments was relatively small, and the fall of the main fragment happened into the water, so the impact mechanism of seismic waves, apparently, less powerful than the acoustic from

explosion and flyover. This can be approved by analysis of seismic data from seismic stations close to the crash site - ARU, ABKAR, BRVK (Fig.7A,C).

The main seismic signal came to the ARU station 3 minutes after the explosion (200 km from the epicenter, the equivalent ground speed 1.1km/s), and to the stations ABKAR and BRVK - 5 minutes after the explosion (600 km from the epicenter, the equivalent ground speed 2km/s). A similar effect of changing the apparent velocity as a function of distance from the crash site was observed in the paper [Tauzin et al 2013]. Therefore, if considering the mechanism of formation of the seismic signal due to the passage of a supersonic body, for the calculation of the horizontal velocity it must be taken into account the delay due to sound propagation from height of flight (30-60km) to the ground ( $\sim 2$  min, Fig.7). Taking into account the delay for the calculation of the seismic disturbance ground speed results to the estimates of the seismic waves speed 3.3km/s, known for large distances [Tauzin et al 2013], the same for all three seismic stations (ARU, ABKAR, BRVK). This indicates good validity of acoustic model for the formation of the main source of the seismic signal in this case.

In this model, the source of the acoustic signal is not the point of the fall, but the entire flight path of the meteorite [Edwards et al 2008], and the wave itself can be considered axisymmetric, with the front close to the cylinder (at small distances from the epicenter). In this case, we can assume that the seismic disturbance signals have axial symmetry, and the signal at the point ABKAR-bis (its place corresponds to symmetric reflection of position of ABKAR seismic observatory relative to the path of the meteorite) (Fig.7A), is expected to be similar to the signal at the point ABKAR.

Usually it is assumed that the fine structure of the signal (its main spectral components) is significantly affected by Earth topography and characteristics at the measurement point [Edwards et al 2008], but the envelope of the seismic signal and the group delay should correlate reasonably well at the same distances and axial angles to the meteorite trajectory, which allows to estimate with good accuracy the delay of the seismic signal at ABKAR-bis point, located almost under the EKB-radar observation area and consider it repeating ABKAR seismic signal.

By estimating acoustic velocity from the MSIS model temperature profile (Fig.6.B), we can estimate the propagation time of acoustic disturbance caused by the propagation of the supersonic seismic wave from the ground to the E-layer heights (100 km, 5 minutes). Due to the high speed of seismic wave the propagation direction of the acoustic wave (determined by the relation between sound speed and the speed of the source) is almost vertical. Comparison of calculated delays with experimental observations (Fig.7B, C) shows good consistency. Limited range of the area where observation of

scattering is possible in E-layer (Figure 6) is also consistent with the model.

The effect of propagating seismic wave causes the formation of inhomogeneities in the ionospheric plasma, that are experimentally observed after the earthquakes [Maruyama et al 2012] and has a theoretical explanation [Maruyama and Shinagawa 2014]. It should be noted that the vertical amplitude of the seismic waves observed after the earthquake Tohoku about 300 times higher than from the meteorite 'Chelyabinsk'. For the linear mechanism of formation of acoustic and ionospheric irregularities it allows us to expect the amplitude of the perturbations of the electron density 300 times smaller than for perturbations accompanying Tohoku earthquake. Characteristic vertical scale inhomogeneities, calculated from the period of the seismic variations at the station ABKAR and sound speed in the ionosphere, is about 600-1000 meters.

At Fig.8 it is shown suggested mechanism of the observed effect that explains delays between different observations.

According to our proposed interpretation of the observed effects in the E-layer of the ionosphere in the first 25 minutes after the meteorite explosion, the effect is a superposition of known or previously observed effects (Fig.8).

Acoustic signal caused by the flyover of the meteorite in the upper atmosphere, after 2 minutes of flight and explosion formed a seismic source on the ground, which elongated with the projection of the meteorite's trajectory, by analogy with [Edwards et al 2008]. Seismic waves propagate from the source with speed of about 3.3 km/s [Tauzin et al 2013], forming in the process of their propagation almost horizontal front of acoustic wave that propagates almost vertically, by analogy with [Maruyama et al 2012]. As a result of interaction of acoustic wave with the ionized component a quasi-periodic inhomogeneity of the electron density is formed with spatial scales defined by period of seismic waves and vertical velocity of the acoustic wave in the ionosphere, by analogy with [Maruyama and Shinagawa 2014]. When the seismic signal reaches the range 400-600km (4-5 min after the explosion of a meteorite) it is observed by seismic observatories ABKAR and BRVK. According to the acoustic wave propagation model, the delay between observations of vertical ionospheric irregularities due to the passage of an acoustic signal at E-layer heights generated by seismic source and the seismic signal under this ionospheric point is 4-5 minutes.

According to our interpretation the effect of sharp increase in Doppler velocity of irregularities elongated with the magnetic field, detected by EKB radar at the 9-11 minute after the meteorite explosion may be associated with additional growth of the irregularities elongated with the Earth magnetic field due to the passage of the secondary acoustic wave through the ionospheric plasma (or corresponding quasi-vertical traveling of ionospheric plasma inho-



mogeneties) in the presence of strong enough background ionospheric electric field. The distance to the bursts in Doppler velocity is determined by the implementation of the necessary conditions for scattering from field-aligned irregularities in E-layer. Time of occurrence of the bursts (delay from the meteorite explosion time) is associated with the passage of an acoustic wave through the region of the effective aspect scattering.

The mechanism of such amplification of field-aligned E-layer irregularities in the presence of an acoustic wave at the moment is not clear. Nevertheless, as possible growth mechanisms for these elongated irregularities may be used the following models or theirs combination: the electric field amplification in the presence of heavy ions in sporadic-E and acoustic wave [Liperovsky et al 1997]; the growth of gradient-drift instability [Rogister and D'Angelo 1970] in the presence of vertical gradients in the electron density caused by the propagation of acoustic waves; the growth of Kelvin-Helmholtz instability and large electric fields in E-layer [Benrhardt 2002] in the presence of fast propagating acoustic wave front.

## 4 Conclusion

This paper presents the properties of ionospheric irregularities elongated with Earth magnetic field during the first 25 minutes after the fall of the meteorite 'Chelyabinsk' experimentally observed with EKB radar of Russian segment of the SuperDARN.

It is shown that 40 minutes before meteor fall the EKB radar started to observe powerful scattering from irregularities elongated with the Earth magnetic field in the F-layer. Scattering was observed for 80 minutes and stopped 40 minutes after the meteorite fall (Fig.1). Most probably this effect is caused by presence of auxiliary electric field.

During 9-15 minutes after the meteorite fall at ranges 400-1200 km from the explosion site a changes were observed in the spectral and amplitude characteristics of the scattered signal. This features were the sharp increase in the Doppler frequency shift of the scattered signal corresponding to the Doppler velocities about 600 m/s (Fig.6) and the sharp increase of the scattered signal amplitude(Fig.5). This feature was detected in the data processed by the three currently used methods of SuperDARN signals - FitACF, FitACFex2 and LMFit. This allows us to conclude that we detected the growth of smallscale ionospheric irregularities elongated with the Earth magnetic field at E-layer heights.

Joint analysis with the seismic data and numerical modeling shows that the observed effect is connected with the passage of secondary acoustic front

formed by supersonic seismic ground wave from the 'Chelyabinsk' meteorite in the presence of a sufficiently high background electric field. The secondary acoustic wave is formed a supersonic seismic ground wave caused by the explosion of a meteorite and its passage. Under this explanation, the distance to bursts of Doppler velocity is determined by the aspect sensitivity of scattering process in the E-layer and the geometry of the Earth magnetic field. Moments of the bursts in Doppler shift (delay them from the meteorite explosion moment) are associated with the passage of an acoustic wave through the region of the effective aspect scattering.

As a possible explanation the growth of elongated ionospheric irregularities may be caused by the passage of the high-speed acoustic wave in the ionosphere in the presence of high enough background electric field. The mechanism of such gain of field-aligned E-layer ionospheric irregularities at the moment is not clear and requires detailed investigation.

## Acknowledgments

This work was supported by the RFBR grant No 14-05-00514a. We are grateful to IRIS network for providing data of seismic observatories ARU, ABKAR and BRVK. The authors are grateful A.Lyahov and T.Loseva (IDG RAS) for useful discussions.

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Point name	N	E	Distance	Type
ABKAR	49.256	59.943	630km	Seismic station
BRVK	53.058	70.283	670km	Seismic station
ARU	56.430	58.562	220km	Seismic station
EKB	56.430	58.562	220km	Coherent decameter radar
METS	54.508	64.266	240km	Trajectory start, h=91km
METE	54.922	60.606	0km	Trajectory end, h=15km

Table 1: Coordinates of main instruments and points used for data analysis



Figure 1: EKB radar field-of-view and trajectory of meteorite 'Chelyabinsk', its explosion (1) and fall(2).

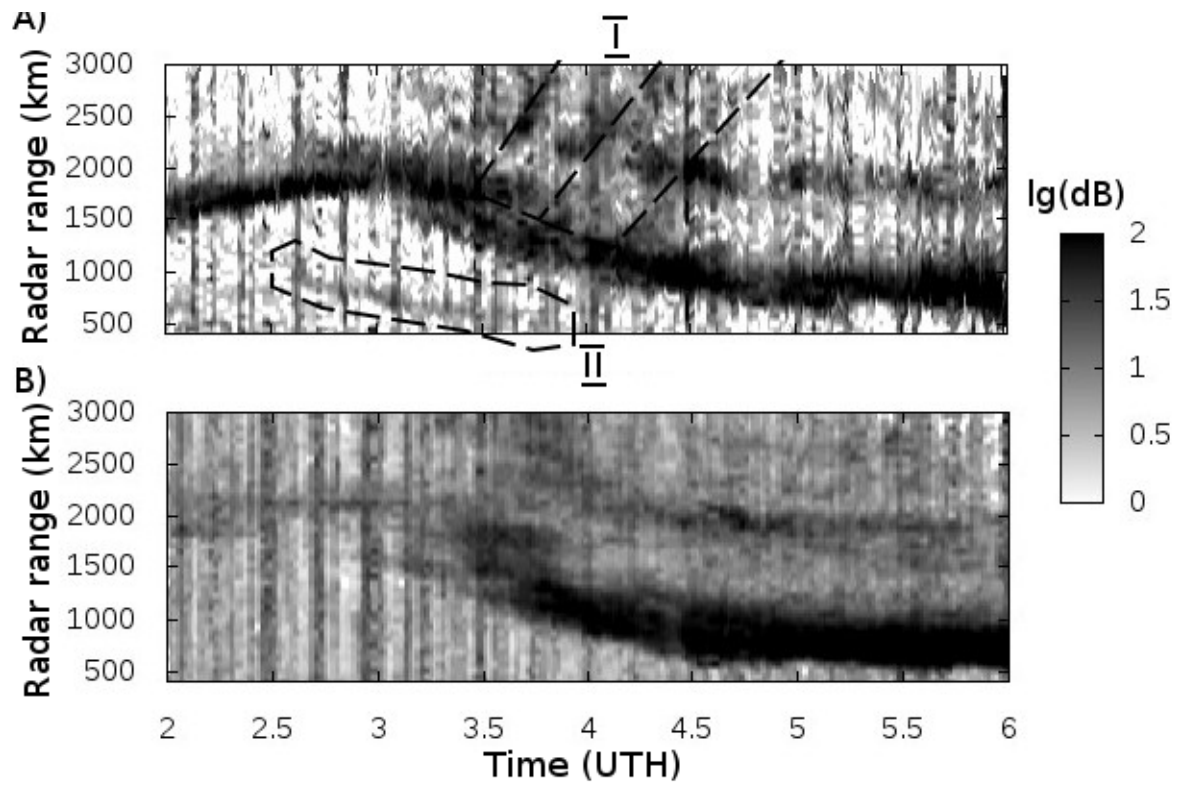


Figure 2: Average (over the field-of-view azimuths) received signal power from EKB radar, as a function of radar range and time. A) - during the day of the meteorite fall 15/02/2013; B) - averaged over the reference days 9-12, 18/02/2013.



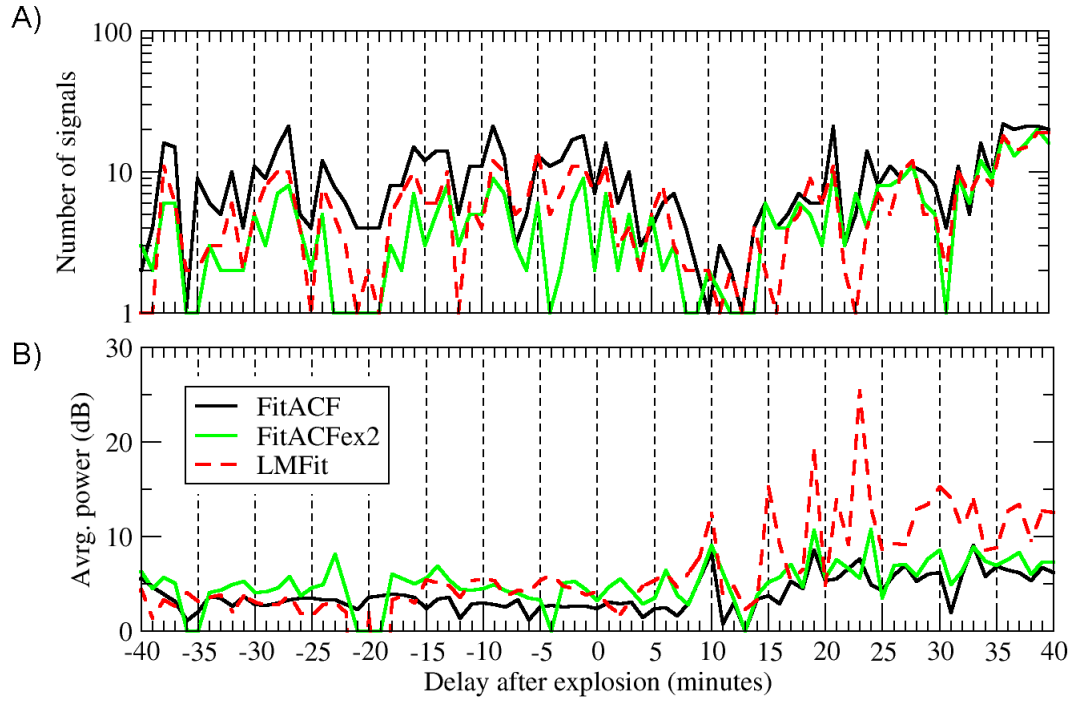


Figure 3: The result of statistical analysis of the EKB radar data in the range of distances 500-1200km in times close to the time of the explosion. Calculations were carried out by three algorithms - FitACF, FitEx2 and LMFit. A) - the amount of 'good' data per 1 minute that can be processed B) - average power of the signal calculated from the 'good' data.

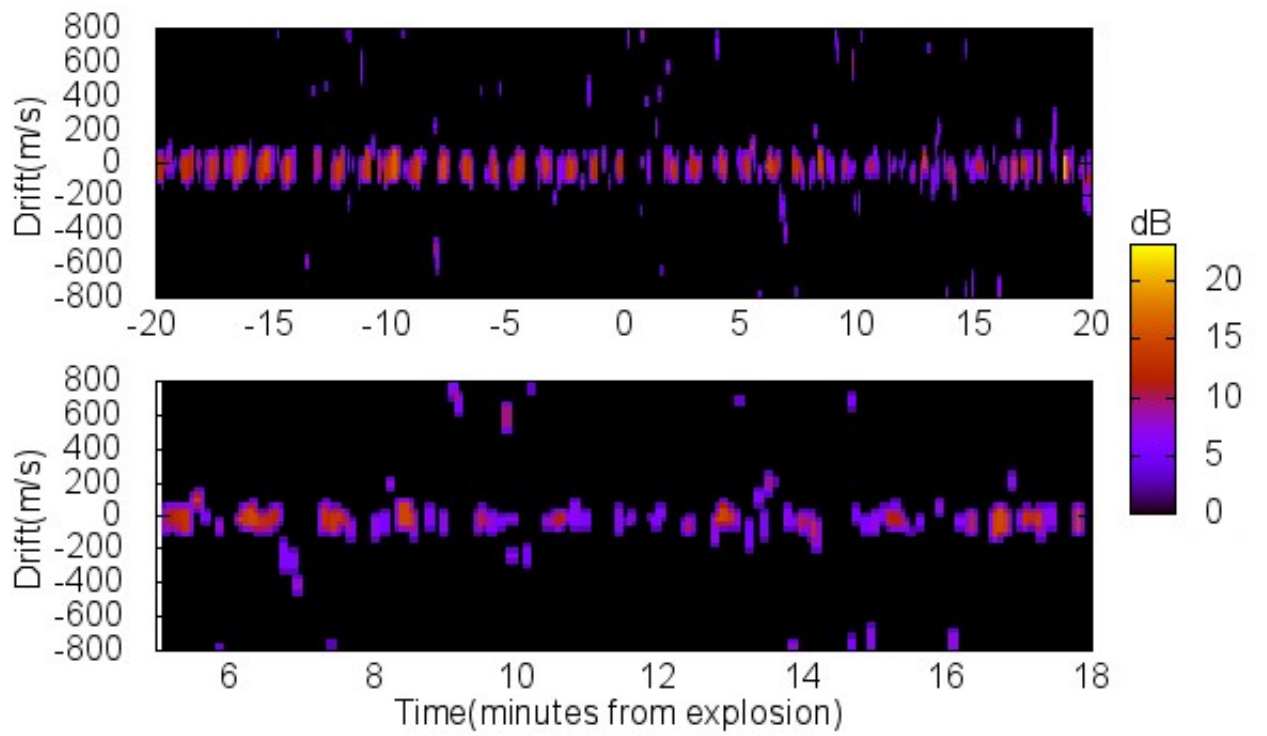


Figure 4: Mean spectral shape of scattered signal in the range 800-1200km from the radar, as a function of delay from explosion moment. Frequency is given in Doppler drift (m/s) units.

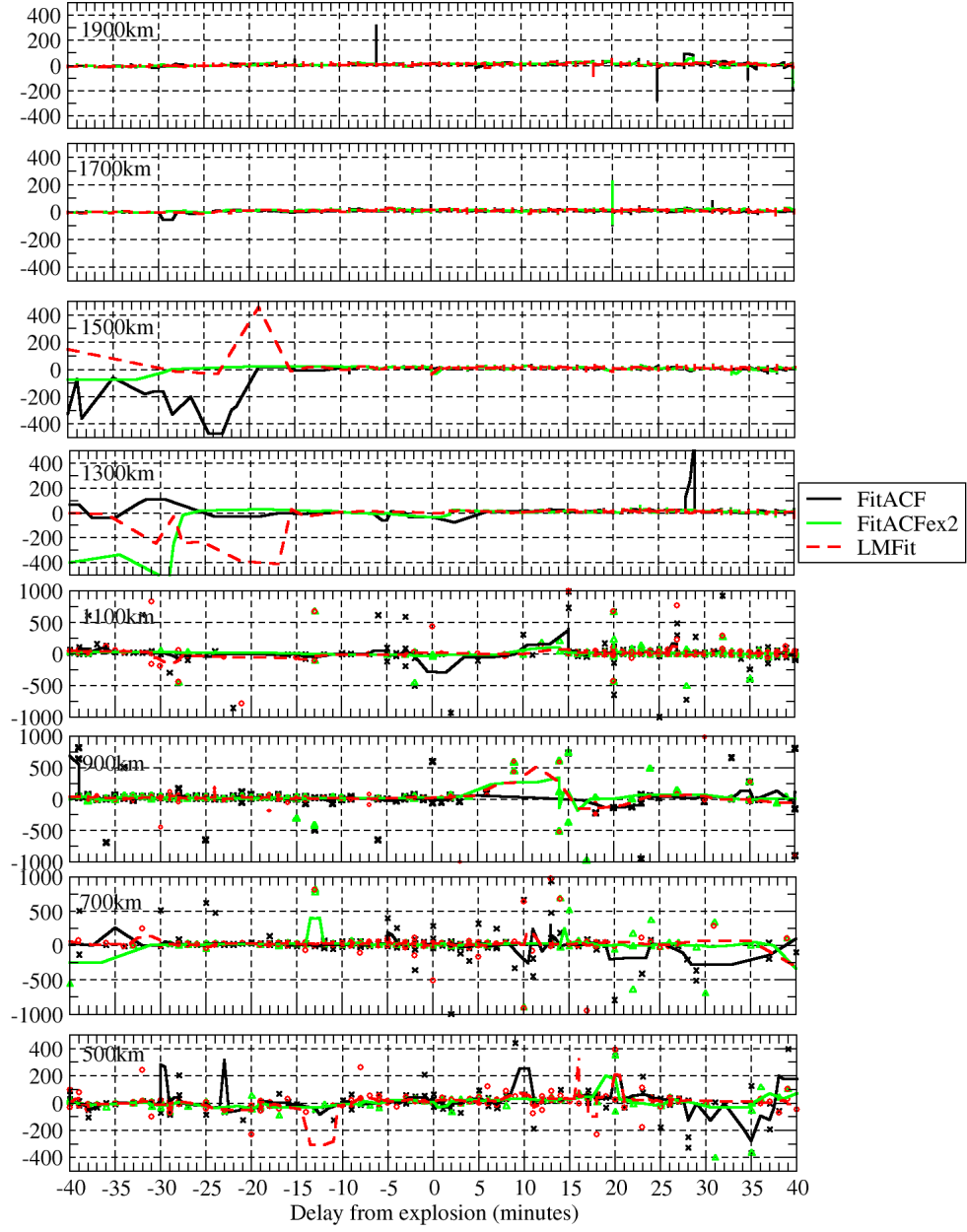


Figure 5: Doppler velocity, calculated from the scattered signal, as a function of delay after the explosion and distance from the EKB radar, calculated by FitACF, FitACFex2 and LMFit programs. Circles, triangles and crosses represent the calculated values, lines - their medians over the 4 adjacent values

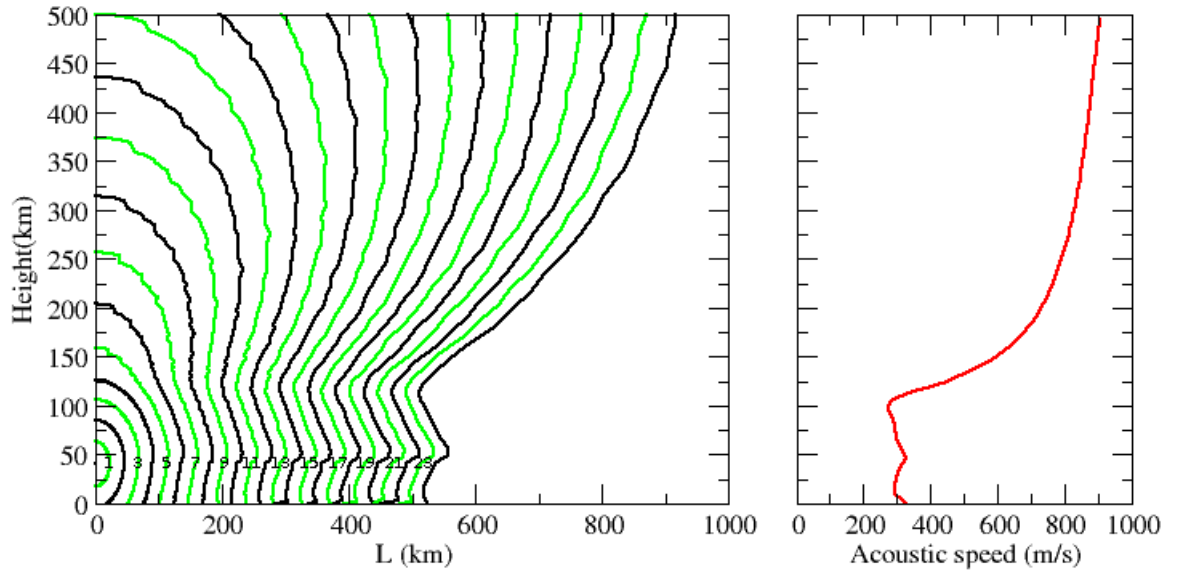


Figure 6: A) - The model of propagational delay of the acoustic signal at different heights and distances from the source, measured across the meteorite trajectory (source height 41km), contour lines every 1 minute; B) - the profile of sound speed in the ionosphere as a function of height, used for modeling.

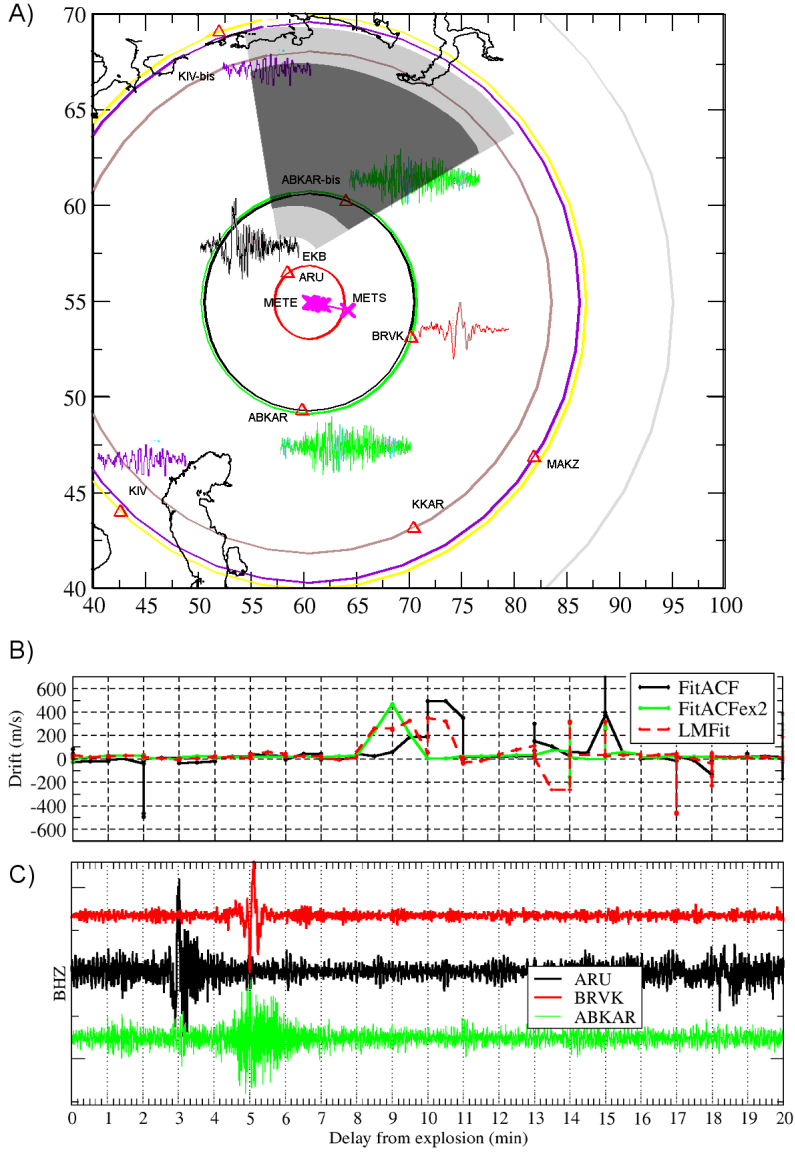


Figure 7: A) - The geometry of seismic observations, B) - Doppler velocities of ionospheric irregularities according to radar EKB, computed by three algorithms - FitACF, FitACFex2 and LMFit, as a function of delay after the meteorite explosion, and C) - vertical seismic oscillations as a function of delay after the meteorite explosion. ABKAR-bis and KIV-bis - points that are symmetrical to observatories ABKAR and KIV relative to the meteorite trajectory. Light gray sector shows field-of-view of the EKB radar, the dark gray sector - the range of distances that meets conditions for observation of scattering from the E-layer irregularities.

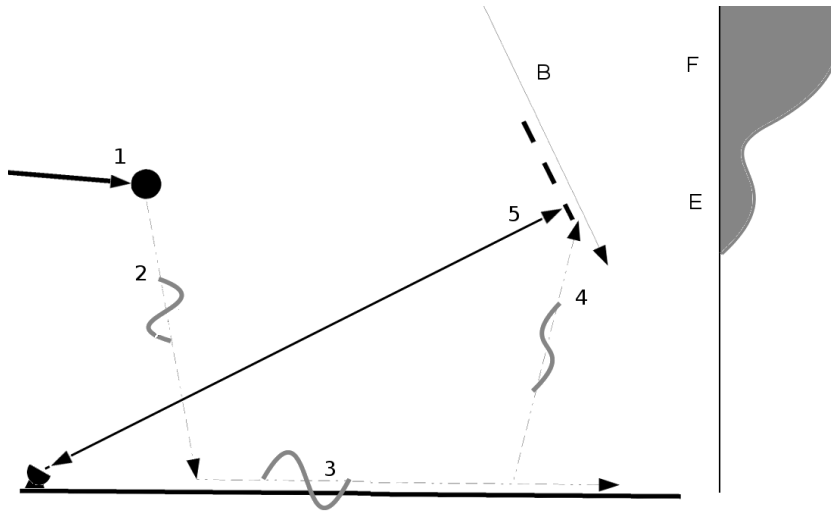


Figure 8: The proposed scheme to explain the observations with the EKB radar. 1-trajectory of a meteorite; 2-primary acoustic wave; 3-seismic wave; 4 - secondary acoustic wave; 5- field-aligned scattering of the EKB radar signal at E-layer heights.